Annual Report

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14. ABSTRACT
This proposal aims to develop the electrically driven single photon sources for applications in quantum computing and quantum cryptography. The development of single photon devices is an important issue and has much potential in the field of modern photonics and optical technology in conjunction with nanotechnology.

15. SUBJECT TERMS
Optoelectronic Materials, nanoelectronics

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1. Objectives

In this project, the overall objectives are developments of electrically driven single photon source that operate near room temperature by using epitaxially grown GaN nanostructures. In order to realize the electrically driven single photon source operating near room temperature, we will grow high-quality GaN quantum dots embedded in AlN thin films, and fabricate single photon emitting tunnel diodes that have GaN quantum dots in a microcavity structure with nano-sized aperture. Single electron and hole injection, which is the precondition for single photon emission, will be driven by using Coulomb blockade effect in GaN quantum dots surrounded by AlN tunnel barriers. Figure 1 shows a schematic of the proposed single photon emitting diode.

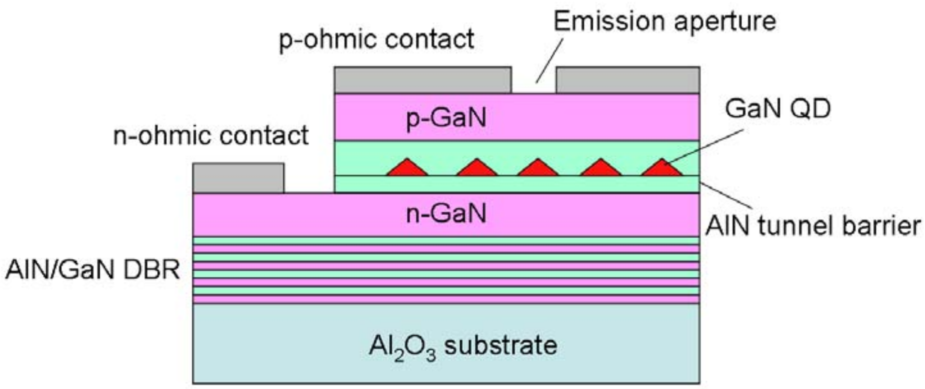

Fig. 1. Schematic of the proposed single photon emitting diode

2. Status of effort

We have designed the structure for single photon emitting devices that have GaN nanostructures embedded into the microcavity structure. The design of the device structure was accomplished using Rsoft FULLWAVE simulation. We have grown GaN quantum dots with small size and low density using metalorganic chemical vapor deposition (MOCVD). Additionally, Al(Ga)N/GaN heterostructure with high quality are grown because it is important to achieve the high performance of single photon emitting diodes. In order to develop an efficient single photon source, an optical cavity structure will be applied. We have optimized the growth condition of Al(Ga)N/GaN DBR for the microcavity structure.

3. Abstract

We have grown InGaN quantum dots on GaN layer by the Stranski-Krastanow (S-K) growth mode using MOCVD with various conditions for small size as a few nanometers and low density of ~10^9/cm^2. Since the growth of InGaN quantum dots is very sensitive to the growth condition, the formation of InGaN quantum dots can be controlled by growth parameter such as the growth temperature, time and the flow rate of MO sources. Especially, InGaN quantum dots with small size and low density are required to realize electrically driven single photon sources. InGaN quantum dots are characterized by using AFM and photoluminescence (PL) measurement to analyze the structural and optical properties. Additionally, it is required to embed GaN quantum dots into the microcavity with a small volume and high quality factor for a high internal quantum efficiency and photon collection efficiency of single photon emitters. We have optimized Al(Ga)N/GaN distributed Bragg Reflectors (DBRs) for a cavity mode and 38% of reflectivity can be obtained using 5 pairs of $Al_{0.2}Ga_{0.8}N$/GaN DBR instead of 30 pairs.

4. Personnel Supported

Name	[redacted]	Affiliation / Department	Position (Status) / Field of Study/ Final Degree	Start Date / End Date	Project Participation Ratio (%)
Park, Seong-Ju	[redacted]	GIST	Professor	20080801	10
		MSE	Semiconductor/ Ph.D.	20100731	
Cho, Chu-Young	[redacted]	GIST	Ph.D. course	20080801	6
		MSE	Semiconductor/ M.S.	20100731	
Lee, Sang-Jun	[redacted]	GIST	Ph.D. course	20080801	6
		MSE	Semiconductor/ M.S.	20100731	
Hong, Sang-Hyun	[redacted]	GIST	Ph.D. course	20090801	6
		MSE	Semiconductor/ M.S.	20100731	
Park, Seung-Chul	[redacted]	GIST	M.S. course	20080801	5.56
		MSE	Semiconductor / B.S.	20100731	
Jeong, Seung-Hui	[redacted]	GIST	Assistant	20080801	5
		MSE	Electronics/B.E.	20100731	

5. Publications

"Growth of height-controlled InGaN quantum dots on GaN" – submitted to Journal of crystal growth

"Height-controlled InGaN quantum dots and light-emitting diode applications" – submitted to Semiconductor Science and Technology

“Effect of electron-blocking layer on efficiency droop in InGaN/GaN multiquantum well light-emitting diodes" – Han *et al*., Applied Physics Letters, 94, 231123 (2009)

“Enhanced light extraction efficiency of GaN-based light-emitting diodes with indium tin oxide/air hole photonic crystal” – submitted to Optics Express

“Enhanced light extraction in light-emitting diodes with photonic crystal structure selectively grown on p-GaN” – submitted to Applied Physics Letters

“Improvement of GaN-based light-emitting diodes using p-type AlGaN/GaN superlattices with a graded Al composition” – paper in preparation

6. Interactions

6th US-KOREA workshop on nanoelectronics
Date: 19-20 May 2009

Place: Hanyang University, Seoul, Korea
Title: Gallium Nitride UV Single Photon Source
Abstract: The overall objectives of our research are developments of electrically driven single photon source that operates near room temperature by using epitaxially grown GaN nanostructures. In order to realize the electrically driven single photon source operating near room temperature, we first grow the high-quality InGaN quantum dots (QDs) embedded in AlN thin films. For the InGaN QDs embedded in AlN films, a high quality of AlN layer was obtained at high temperature by using metal-orgranic chemical vapor deposition (MOCVD). After the growth of AlN epilayer, InGaN QDs on an AlN epilayer were demonstrated by the Stranski-Krastanow (S-K) growth mode. The structural and optical properties of InGaN QDs were analyzed by using atomic force microscopy (AFM) and photoluminescence (PL) measurement, respectively. In addition, we demonstrated a cavity mode by using AlN/GaN pairs as distributed Bragg reflectors (DBRs). AlN/GaN DBRs was optimized by using a simulation program (Rsoft FULLWAVE), and the thickness of each epilayer can be calculated by following equation, $d = \lambda/4n$, where d and λ are the thicknesses of epilayer and wavelength, respectively. The characteristics of the emission from InGaN QDs embedded in a microcavity will be discussed.

7. Inventions

None

8. Honors/Awards

Academic awards of Korean Vacuum Society (2009)

9. Archival Documentation

1) Simulation of the devices

The design of device structure is accomplished using Rsoft FULLWAVE simulation. Figure 2 (a) and (b) show the simulation structure for 30 pairs of AlGaN/GaN DBR and simulated transmittance. The composition of Al is 20 % in AlGaN layer and the thickness of each layer can be calculated, respectively for the target wavelength of 400 nm. The simulated transmittance is lowest at wavelength of 400 nm as shown in Fig. 2 (b). This indicates that the reflectivity of 30 pairs of AlGaN/GaN DBR is over 90%.

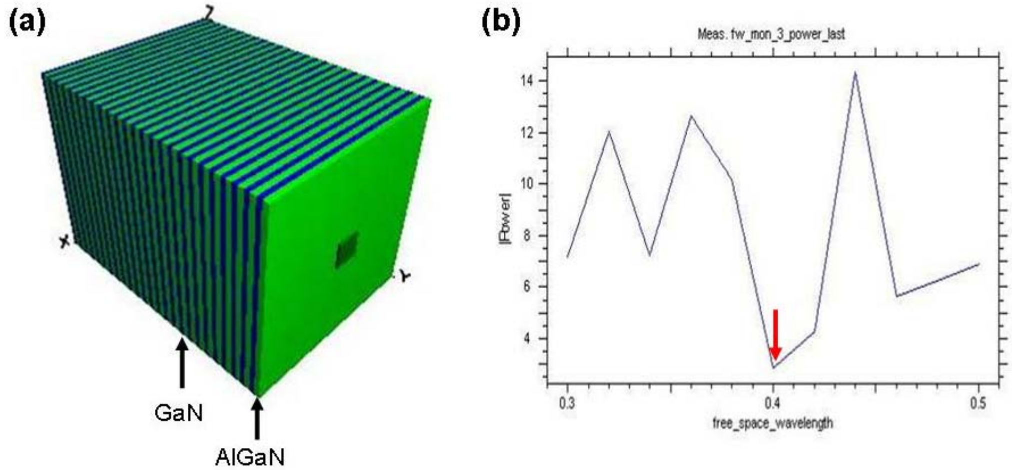

Fig. 2. (a) Simulation structure for 30 pairs of AlGaN/GaN DBR and (b) simulated transmittance

Figure 3 (a) and (b) show the refractive index profile of device structure and the intensity as a function of wavelength. The position of quantum dots layer is 122 nm from top of cavity. Based on the structure as shown in Fig. 4 (a), the resonant wavelength is 400 nm inside the cavity. Therefore, the simulation result is comparable to the calculated result.

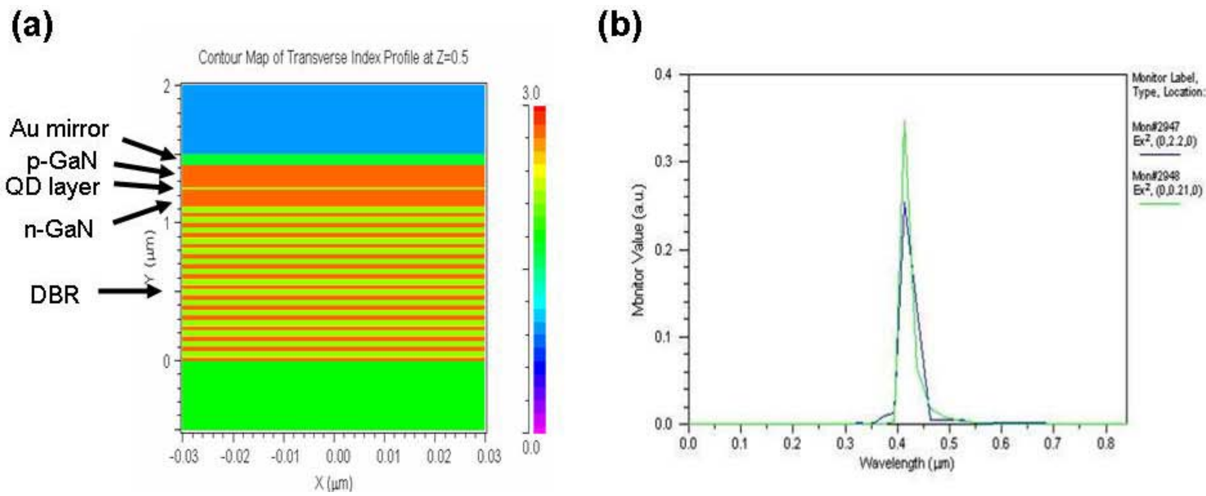

Fig. 3. (a) Refractive index profile of device structure and intensity as a function of wavelength

2) Growth and characterization

Figure 4 shows AFM images of InGaN quantum dots grown on GaN layer by Stranski-Krastanow (S-K) growth mode. The formation of quantum dots is incomplete at the growth time of 7 sec. Total density of InGaN quantum dots is increased with increasing the growth time. The size and height of InGaN quantum dots are 20~30 nm and 1~2 nm, respectively indicating that aspect ratio is small.

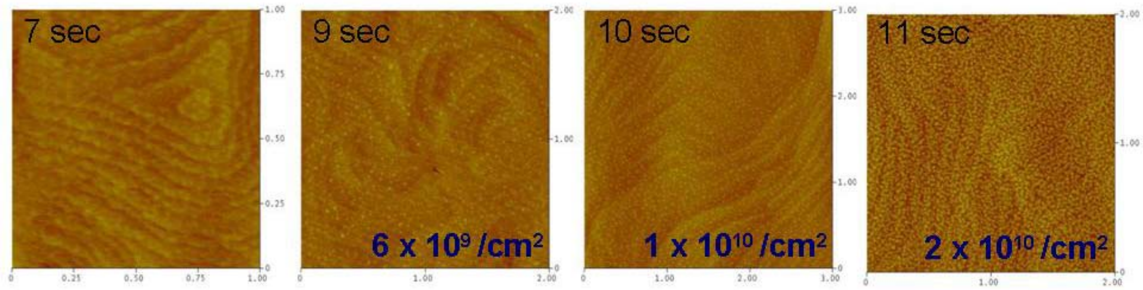

Fig. 4. AFM images of InGaN quantum dots grown on GaN layer

Figure 5 (a) and (b) show photoluminescence (PL) measurement of InGaN quantum dots with single layer at 300K (room temperature) and 6K, respectively. The PL peak at 300K shows the wavelength nearby 400 nm. The P-1 cannot be measured at RT since carriers in the wetting layer vanish at nonradiative recombination centers such as defect.

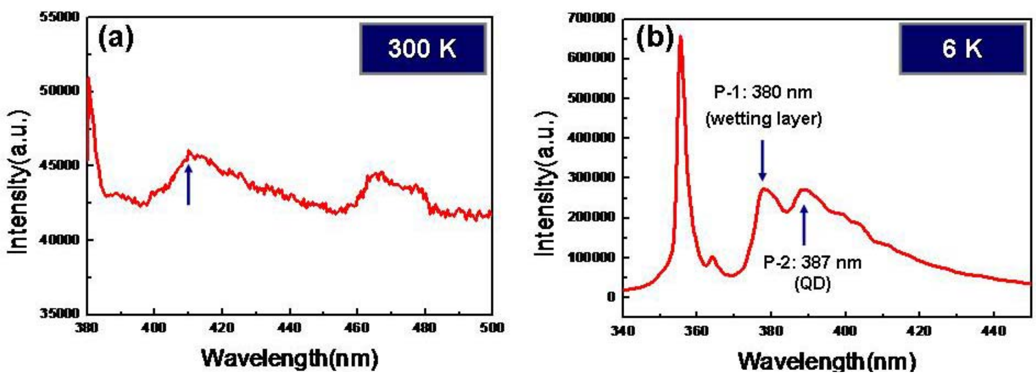

Fig. 5. PL measurement of InGaN quantum dots with single layer (a) at 300K and (b) at 6K

Figure 6 (a) and (b) show the schematic diagram of InGaN quantum dots with 5 pairs and PL measurement of this sample as a function of excitation power. There is no blue shift with excitation power. This result is attributed to the small Quantum-Confined Stark Effect (QCSE) and negligible piezoelectric field in InGaN quantum dots.

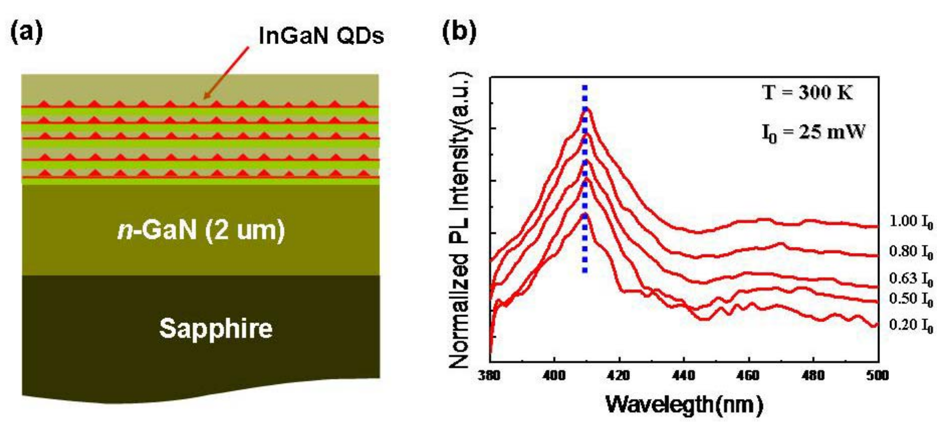

Fig. 6. (a) Schematic diagram of InGaN quantum dots with 5 pairs and (b) PL measurement as a function of excitation power

Figure 7 shows SEM images of 5 pairs of AlN/GaN and AlGaN/GaN DBR structures. In case of AlN/GaN DBR, there is a crack on the surface with growth pressure. This is due to the large lattice mismatch between GaN and AlN. However, AlGaN/GaN DBR structures have a smooth surface without crack because the lattice mismatch is reduced.

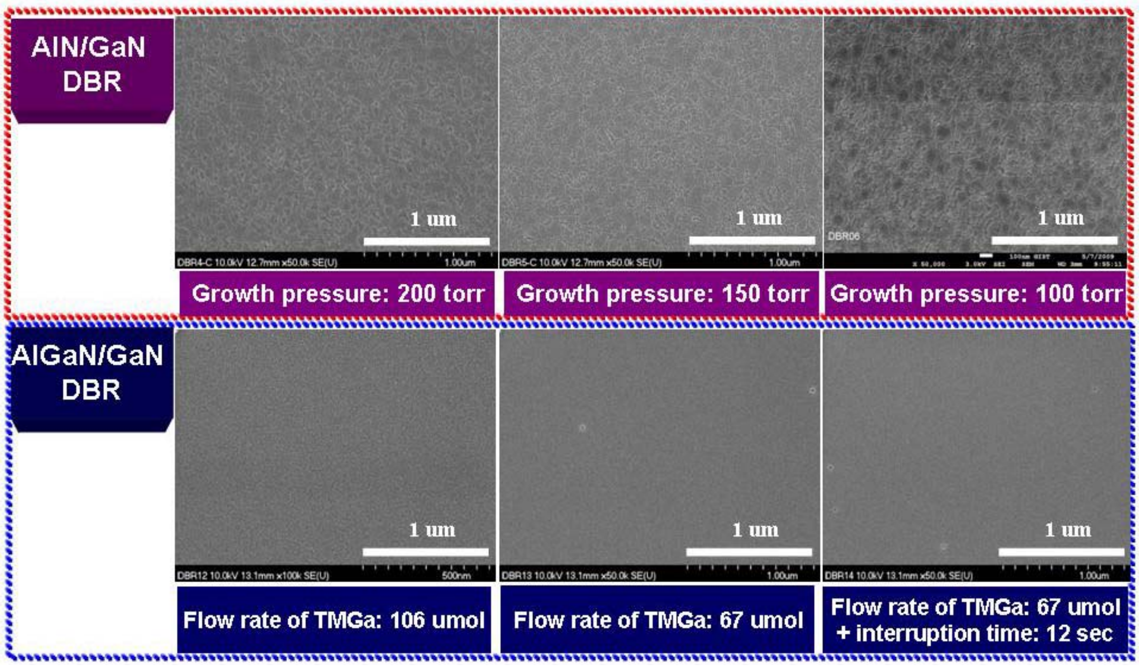

Fig. 7. SEM images of 5 pairs of AlN/GaN and AlGaN/GaN DBR structures

Figure 8 shows XRD measurements of AlN/GaN and AlGaN/GaN DBR structures. The thickness of each period can be calculated based on the oscillation peak. Additionally, the thickness of one period in $Al_{0.2}Ga_{0.8}N/GaN$ DBR should be 81.2 nm for target wavelength of 400 nm. Therefore, the optimized thickness can be obtained by controlling the growth conditions for 400 nm.

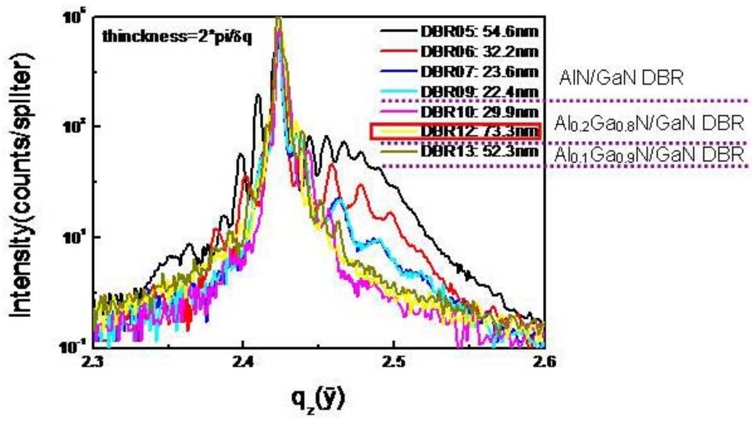

Fig. 8. XRD measurements of AlN/GaN and AlGaN/GaN DBR structures

Figure 9 (a) and (b) show the reflectivity of DBR structures. The 5 pairs of $Al_{0.2}Ga_{0.8}N/GaN$ DBR instead of 30 pairs show the highest reflectivity of 38% as shown in Fig. 4 (a). This value is higher than the reported reflectance of 5 pairs of $Al_{0.2}Ga_{0.8}N$/GaN DBR structure. The stop band width of $Al_{0.2}Ga_{0.8}N$/GaN DBR structure is 7 nm.

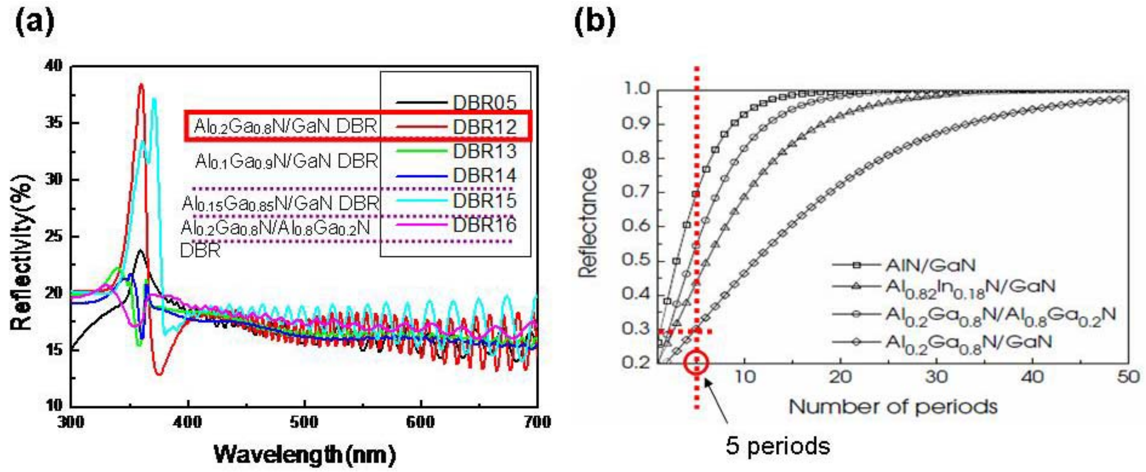

Fig. 9. (a) reflectivity of DBR structures as a function of wavelength and (b) reflectance of DBR structures with number of periods (reported)

For the high reflectivity of $Al_xGa_{1-x}N$/GaN DBR, the pairs & Al composition should be increased. Figure 10 shows SEM images of 30 pairs of $Al_{0.2}Ga_{0.8}N$/GaN DBR structure with growth interruption time. The surface morphology of DBR is improved as the growth interruption time was increased due to the enhanced surface mobility of Al adatom.

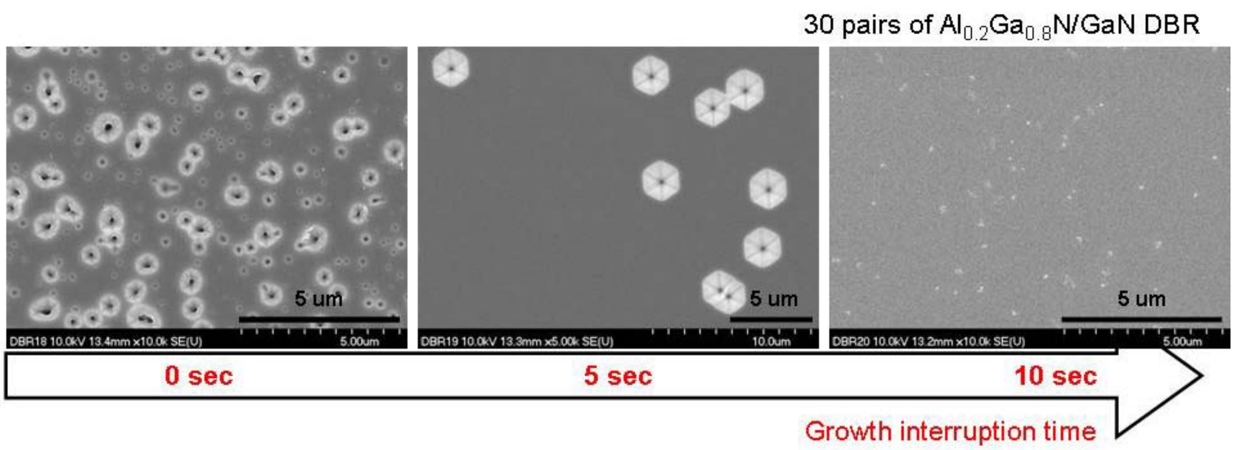

Fig. 10. SEM images of 30 pairs of $Al_{0.2}Ga_{0.8}N$/GaN DBR structure with growth interruption time

10. Software and/or Hardware (if they are specified in the contract as part of final deliverables)

None